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# Research on Shallow Stress Variation before and after the 2011Japan Earthquake in Bohai Strait and Its Adjacent Area

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# Research on Shallow Stress Variation before and after the 2011Japan Earthquake in Bohai Strait and Its Adjacent Area

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**Abstract:** To identify the geostress adjustment process of Japanese earthquake in Bohai Strait and its surrounding area, based on the data of 10 shallow hydraulic fracturing drills in the axis of the channel acquired from 2012 to 2014, the dispersed point charts and regression formulas of each parameter with depth were established and calculated. The results showed that between 2010 and 2014, the horizontal differential stress first decreased and then increased, and the direction of stress first rotated clockwise and then counter-clockwise. Therefore, coseismic and postseismic displacement triggered by Japanese earthquake caused shallow extensional effect which lasted from 2011 to 2012 in research area, and shallow stress didn't return to the original level until 2013. During the period of shallow stress reduction, the fault zone of seismic hazard was reduced as the compressive strain energy was released, while during the period of sustained stability after stress recovery the NWW fault zone had the maximum seismic hazard than NNE. The results were of great significance for research on shallow stress accumulation caused by earthquake, fault activity and the construction of tunnel in Bohai Strait and its surrounding area.

## 1. Introduction

On March 11, 2011, an earthquake of Ms 9.0 struck off the east coast of Japan, with the epicentre located in 38.1 °N and 142.6 ° E and focal depth about 10 km [1], which intrigued widespread concern because of its enormous impact. The influence of the earthquake on the eastern China had been studied extensively, which mainly focused on the research of coseismic and postseismic deformation[2-4], the simulation of the coulombic stress variation in fault zones [5,6], postseismic regional stress state statistics [7], and the adjustment analysis of stress direction [8]. However, the research conclusions were very different.

The variation of the coulombic stress caused by the earthquake in Japan could be inferred from simulation, but the more important factor was to obtain the absolute stress level of the region. The superficial and shallow stress data could be acquired by in-situ stress measurement. The effect of the stress adjustment after the earthquake had been paid wide attention by scientists and engineers.

The ten shallow drillings were implemented in the Bohai strait area from 2012 to 2014 to guarantee the successful implementation of sea-crossing channel engineering. On the basis of this data, this paper first collected the data of 12 drill holes which belong to the area of Beijing, Tangshan, Tanlu fault zone, and then analysed the change of the stress level, relative magnitude of horizontal differential stress, stress direction and stress state with time and depth. Finally it discussed the post seismic risk of fault zone NNE and NWW.

## 2. Data

According to the results of field survey, 5 shallow land drills named ZK-KX1～ZK-KX5 were implemented, which obtained 7 groups of empty core inclusion data with depths ranging from 65m to 130m in 2012. The 2 shallow drills named ZK-1～ZK-2 in Liaodong island and 3 shallow drills named ZK-3～ZK-5 in Miaodao islands sea area were implemented respectively in 2013 and 2014, and a total of 19 sets of hydraulic fracturing measurements between 20m and 160m depth were obtained. Besides, we collected 271 sets of hydraulic fracturing data with depth ranging from dozens of meters to nearly a kilometer, which belong to 12 holes published in recent years in the adjacent area[9]. Figure 1 gave the location of drills and table 1 showed the original measured in-situ stress data.

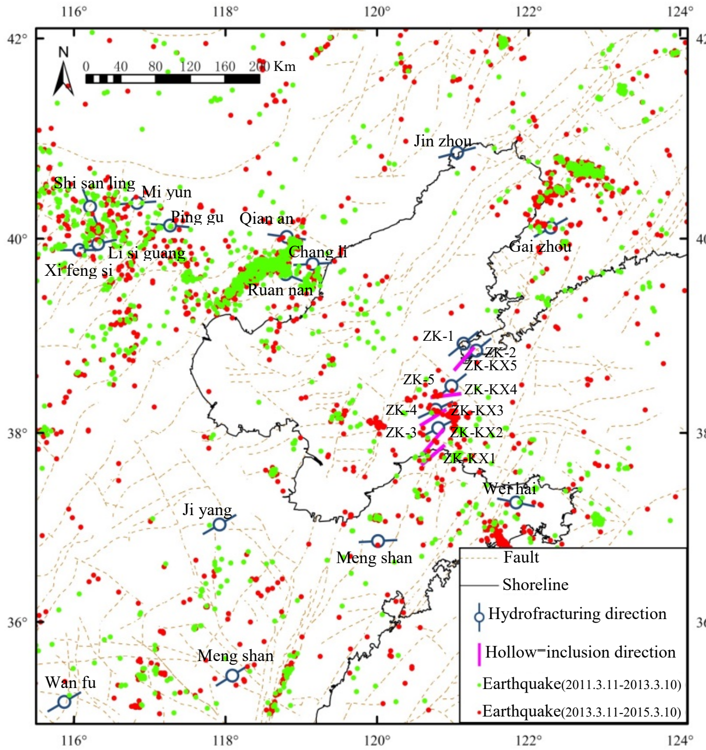


Figure 1 Location of the drill hole and distribution of the stress direction

Table 1 Result of in-situ stress measurements in Bohai Strait

| Name | Depth (m) | $P_b$ (Mpa) | $P_r$ (Mpa) | $P_s$ (Mpa) | $P_o$ (Mpa) | $T_{hf}$ (Mpa) | $\sigma_H$ (Mpa) | $\sigma_h$ (Mpa) | $\sigma_v$ (Mpa) | $\sigma_H$ direction (°) |
|---|---|---|---|---|---|---|---|---|---|---|
| ZK-1 | 20.0 | 6.41 | 5.24 | 4.13 | 0.20 | 1.17 | 6.95 | 4.13 | 0.53 | NE50 |
| | 41.0 | 7.24 | 6.26 | 4.81 | 0.41 | 0.98 | 8.96 | 5.21 | 1.09 | NE61 |
| | 56.0 | 9.72 | 8.39 | 5.83 | 0.56 | 1.33 | 10.64 | 6.53 | 1.48 | NE40 |
| | 65.0 | 10.39 | 8.76 | 6.11 | 0.65 | 1.63 | 10.72 | 6.71 | 1.72 | NE52 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ZK-2 | 25.0 | 6.61 | 5.62 | 4.50 | 0.25 | 0.99 | 7.63 | 4.50 | 0.66 | NE46 |
| | 32.0 | 7.73 | 6.15 | 4.82 | 0.32 | 1.58 | 7.99 | 4.82 | 0.85 | NE52 |
| | 48.0 | 9.61 | 8.37 | 5.22 | 0.48 | 1.24 | 6.81 | 5.22 | 1.27 | NE56 |
| | 60.0 | 11.44 | 9.74 | 6.53 | 0.60 | 1.70 | 9.25 | 6.53 | 1.59 | NE48 |
| ZK-3 | 71.0 | 20.15 | 3.35 | 2.81 | 0.70 | 16.80 | 4.38 | 2.81 | 1.88 | NE62 |
| | 96.0 | 18.20 | 4.63 | 3.64 | 0.94 | 13.57 | 5.35 | 3.64 | 2.54 | NE58 |
| | 116.5 | 23.91 | 5.58 | 4.47 | 1.14 | 18.33 | 6.69 | 4.47 | 3.09 | NE60 |
| | 138.5 | 25.19 | 6.76 | 5.45 | 1.36 | 18.43 | 8.23 | 5.45 | 3.67 | NE72 |
| ZK-4 | 120.0 | 20.65 | 6.12 | 5.42 | 1.18 | 14.53 | 8.96 | 5.42 | 3.18 | NE66 |
| | 130.0 | 23.30 | 6.75 | 5.92 | 1.27 | 16.55 | 9.74 | 5.92 | 3.45 | NE62 |
| | 142.5 | 24.04 | 7.31 | 6.53 | 1.40 | 16.73 | 10.88 | 6.53 | 3.78 | NE67 |
| ZK-5 | 126.5 | 21.11 | 5.78 | 4.72 | 1.24 | 15.33 | 7.14 | 4.72 | 3.35 | NE46 |
| | 140.0 | 21.91 | 6.34 | 5.61 | 1.37 | 15.57 | 9.12 | 5.61 | 3.71 | NE52 |
| | 150.0 | 23.54 | 7.21 | 6.32 | 1.47 | 16.33 | 10.28 | 6.32 | 3.98 | NE56 |
| | 159.5 | 24.93 | 8.32 | 7.16 | 1.56 | 16.61 | 11.60 | 7.16 | 4.23 | NE48 |
| ZK-KX1 | 80 | ---- | ---- | ---- | ---- | ---- | 7.73 | 6.46 | 5.13 | NE62 |
| | 130 | ---- | ---- | ---- | ---- | ---- | 10.07 | 8.26 | 6.18 | NE36 |
| ZK-KX2 | 81 | ---- | ---- | ---- | ---- | ---- | 5.85 | 4.85 | 3.97 | NE40 |
| ZK-KX3 | 75 | ---- | ---- | ---- | ---- | ---- | 5.49 | 4.54 | 3.47 | NE58 |
| ZK-KX4 | 58.7 | ---- | ---- | ---- | ---- | ---- | 5.22 | 4.01 | 4.84 | NE83 |
| ZK-KX5 | 65 | ---- | ---- | ---- | ---- | ---- | 5.85 | 3.91 | 4.65 | NE45 |
| | 120 | ---- | ---- | ---- | ---- | ---- | 6.10 | 3.97 | 4.68 | NE37 |

The depth of ZK1、ZK2、ZK-KX1～ZK-KX5 was calculated from the surface. The depth of ZK3、ZK4、ZK5 was calculated from the bottom of the sea.

## 3. Analysis of stress parameters before and after the large earthquake

The occurrence of a large earthquake could change the characteristics of the stress field around fault and surrounding area, which presented non-uniformity in time and space.

### *3.1 Analysis of maximum and minimum horizontal principal stress distribution with depth*

This paper established the scatter plot and linear fitting results of stress parameters in BoHai Strait (Figure 2). Figure 2 indicated that the depth of the measured points in 2012 and 2014 was generally deeper than that of 2013, and the stress magnitude of each annual measuring point increased linearly with depth, but the overall trend of the three year was not obvious [10]. On this basis, the annual fitting formulas （1）～（3）were established, which was also plotted in figure 2.

$$2012: \quad \begin{cases} \sigma_H = 0.0684H + 1.120 & R = 0.92 \\ \sigma_h = 0.0624H + 0.245 & R = 0.93 \end{cases} \tag{1}$$

$$2013: \quad \begin{cases} \sigma_H = 0.0703H + 5.571 & R = 0.76 \\ \sigma_h = 0.0586H + 2.917 & R = 0.94 \end{cases} \tag{2}$$

$$2014: \quad \begin{cases} \sigma_H = 0.0832H - 2.118 & R = 0.92 \\ \sigma_h = 0.0484H - 0.847 & R = 0.95 \end{cases} \tag{3}$$

Formula (1) ～ (3) showed that the two gradients of the maximum and minimum horizontal principal stress one year after the earthquake were relatively close to each other, which further indicated that the magnitude difference between the two was small. During the two to three years after the earthquake, the gradient of the maximum horizontal principal stress increased slightly, while the gradient of the minimum horizontal principal stress decreased a little. It could be concluded that the difference of the two horizontal principal stress values increased gradually.

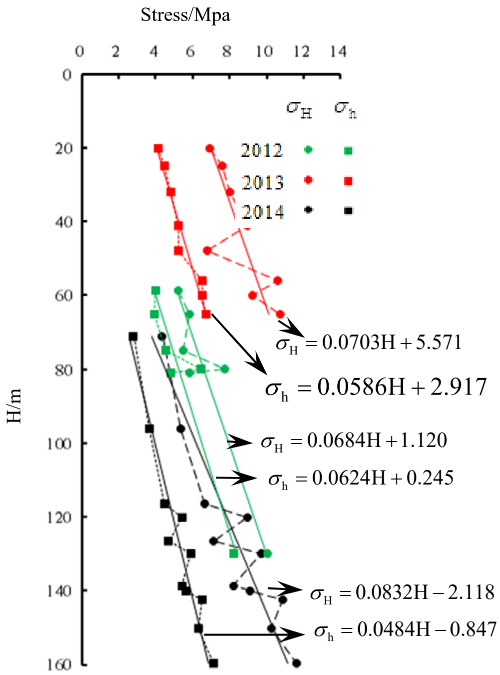


Figure 2 Scatter plot and fitting results of stress parameters in BoHai Strait

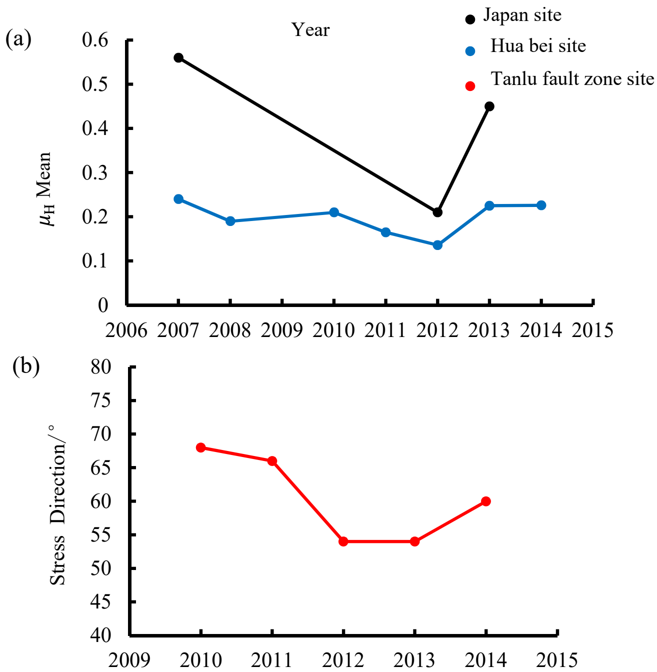


Figure 3 Time variation of the relative size of horizontal differential stress and stress direction

*3.2 Analysis of the relative magnitude of horizontal differential stress with varying time*

The relative magnitude of horizontal differential stress ($\mu_H$) is the index factor of the stress accumulation in strike-slip stress state region, and had no obvious tendency to increase with depth, the larger the value is, the stronger fault activity performs [10].

According to the original stress data, the annual mean values of $\mu_H$ were calculated, as shown in table 2 and depicted in figure 3(a). The figure showed that $\mu_H$ decreased from 0.24 in 2007 to 0.19 in 2008, then increased to 0.21 till 2010. In the following two years, it continued to decline to the minimum of 0.14 in 2012, and then quickly recovered to 0.24 in 2013 and 0.23 in 2014 respectively, which was almost the same with the value in 2007.

Table 2 Mean value of the relative magnitude of horizontal differential stress and stress direction for each year

| Time | 2007 | | 2008 | 2010 | | 2011 | | 2012 | | | | | | | | 2013 | | | | 2014 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Drill Name | J Z | W H | P G | X F S | M S Z8 | M S Z134 | P D | KX1 | KX2 | KX3 | KX4 | KX5 | M Y | R N | L S G | ZK1 | ZK2 | Q A | G Z | ZK3 | ZK4 | ZK5 |
| $\mu_H$ | 0.24 | 0.24 | 0.19 | 0.21 | 0.21 | 0.19 | 0.14 | 0.10 | 0.09 | 0.09 | 0.13 | 0.21 | 0.15 | 0.17 | 0.16 | 0.25 | 0.20 | 0.37 | 0.14 | 0.20 | 0.25 | 0.23 |
| Direction | ---- | ---- | ---- | ---- | 68 | 44 | 87 | 49 | 40 | 58 | 83 | 41 | ---- | ---- | ---- | 51 | 51 | ---- | 61 | 63 | 65 | 51 |
| $\mu_H$ Mean | 0.24 | | 0.19 | 0.21 | | 0.17 | | 0.14 | | | | | | | | 0.24 | | | | 0.23 | | |
| Direction Mean | ---- | | ---- | 68 | | 66 | | 54 | | | | | | | | 54 | | | | 60 | | |

Similarly, the repeated stress measured results in Japan Kamaishi mining area also showed that $\mu_H$ decreased from 0.56 in 2007 to the lowest point 0.21 in 2012, then quickly rose to 0.45 in 2013. Thus the overall trend was consistent with the research, but the gradient was obviously higher than the values of Bohai strait and surrounding areas. The above research indicated that the two regions were affected by the same major geological event, namely, the control and influence of the same earthquake and post-earthquake stress adjustment caused by the big Japan earthquake on March 11, 2011.

*3.3 Analysis of Stress direction and state change with time*

As mentioned in the above, the annual mean values of stress direction are calculated according to the original stress data in the zone of Tanlu fault, as shown in table 2 and depicted in figure 3(b). The figure showed that the overall direction of the maximum horizontal principal stress was NE～NEE in Tanlu fault zone and the surrounding area from 2010 to 2014. Therein, the direction varied firstly counter clockwise from 2010 to 2012 and then clockwise a little from 2013 to 2014, which was almost the same with that in 2012 and 2013. On the whole, the value of stress directional was slightly smaller than that of pre-earthquake.

## 4. Results and discussion

The Japanese Ms9.0 earthquake not only caused great disaster in Japan, but also changed and adjusted the stress characteristics to a certain extent in eastern China, such as stress accumulation degree, stress direction and state. The continuous eastward displacement triggered by coseismic and postseismic Japanese Earthquake produced nearly east-west tension in the northeast China, which was superimposed on the maximum horizontal principal stress (σ1) of NEE-EW direction. Thus, the maximum and minimum horizontal principal stress was reduced and increased respectively, and the difference between them was small in 2012.The $\mu_H$ value of the research area in the earthquake year was lower than that of the year before the earthquake, and was reduced to the minimum in the year after the earthquake, therefore the region was in the lowest energy accumulation at that time. The stress direction of Tanlu fault zone firstly rotates counter-clockwise then clockwise. Since 2012, the gradient of the maximum and minimum horizontal principal stress gradually increased and decreased respectively, and the relative magnitude of horizontal shear stress increased from the minimal value in 2012 to the constant value. The stress direction keep rotating clockwise to NEE60° until 2014 and remained almost stable. All above indicated that the stress adjustment in eastern China was not consistent in time due to the Japanese Earthquake. The period from the year when the Japanese Earthquake occurred to 2013 was the adjustment period of EW tension effect generated by the Japanese earthquake, including the stress reduction period from 2011 to 2012 and the subsequent recovered period. June to July 2012 may be the turning point when the stretching effect was finished in Tanlu fault zone and surrounding area, and the shallow stress changed from releasing state to accumulating state[8].

The large earthquake at the trench had a certain effect on the stress level of the fault zones in eastern China. During the stress reduction period, the stress drop in the EW direction make the stress mole circle move left, which approached the envelope of friction-sliding and coulomb rupture envelope (figure 4). The normal and shear stress of the fault zones reduced, and the compressive strain energy accumulated for a long time was released, and accordingly the seismic risk of the fault zones was reduced. However, the Japanese Earthquake had not completely decoupled the Pacific plate and its overlying Eurasian plate in the entire eastern region of Honshu Island [10]. After the earthquake, the Pacific plate keep diving under the Eurasian plate, and the tension effect produced by the earthquake continued to weaken with time. At the same time the NE thrust force formed by the collision of the Indian plate with the Eurasian plate remains unchanged in the north China region. Under the combined influence of the two, the EW extrusion stress in the northeast China was accumulating again and increasing gradually. On the stress rising stage, both the normal and shear stress on the fault surface increased (figure 5).

In the stress rising period, the amplification of normal stress was larger than that of shear stress in NNE fault zones, and the angle between the direction of NNE faults and maximum principal stress increased, thus the elastic strain energy was accumulating. However, the NWW fault zones was diametrically opposite to NNE fault zones. Moreover the strike of NWW fault zone was basically in accordance with that induced by Pacific plate subducting to the continental edge of east Asia, so the frictional resistance on the fault surface decreases. When the shear stress was greater, the NWW hidden faults in northeast China could slip and induce earthquake in some special places. The amplification of shear stress was larger than that of normal stress in NEE fault zones, and the strike of the fault was nearly parallel to the direction of the maximum principal stress, therefore NEE fault zones might be in tensional dextral strike slip and conjugate with NWW fault zones, which was difficult to accumulate energy. In conclusion, NWW fault zones had the greatest seismic risk in the period of stress rising and after that.

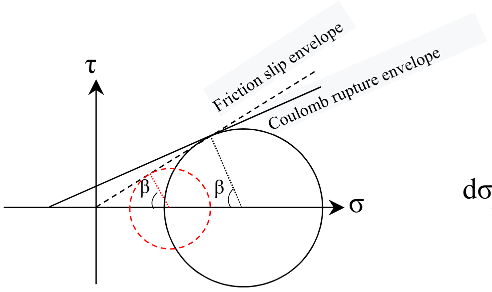


Figure 4 Mohr circle diagram and coulomb Failure Criterion

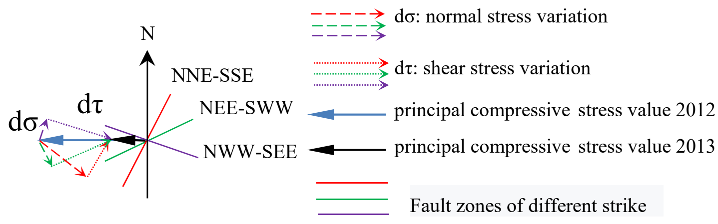


Figure 5 Sketch for the stress change on faults of different strike modified from literature [7]

## 5. Conclusion

From the overall analysis of shallow stress data in eastern north China, it could be concluded that the Japanese Earthquake and post-earthquake relaxation had unloaded the stress in east China to some extent, but by 2013, the shallow stress had returned to the pre-earthquake level, and the seismic risk of NWW faults increases.

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